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**BIOMECHANICAL COMPARISON OF A NOVEL CASTLESS ARTHRODESIS PLATE
WITH T- PLATE AND CROSS PIN TECHNIQUES FOR CANINE PARTIAL CARPAL ARTHRODESIS**

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Declaration of interest

This plate was designed by the author (NJB) in conjunction with the company Orthomed (UK) which owns the design and commercial sale of the castless partial arthrodesis plate system.

Keywords: castless partial carpal arthrodesis canine

Summary

Objectives: To describe a novel canine castless partial carpal arthrodesis plate (par-CA) and its *ex-vivo* biomechanical comparison with T-plate and cross pinning techniques for canine partial carpal arthrodesis.

Methods: The three implant systems were applied to three cohorts of six forelimbs from greyhounds euthanized for reasons unrelated to the study. Intercarpal and carpometacarpal palmar fibrocartilage and ligaments were sectioned. Potentiometers were applied between radial carpal and third metacarpal bones to measure micromotion and limbs loaded at 30% of bodyweight at 1 Hertz for 10,000 cycles on a servo-hydraulic universal testing machine. Following assessment of micromotion limbs were loaded to failure at 20 mm/s and ultimate strength, ultimate displacement and stiffness measured.

Results: The T-plate ($p < 0.01$, ANOVA) and par-CA ($p < 0.01$, ANOVA) had reduced micromotion relative to the cross pin constructs but there was no significant difference between control, T-plate and par-CA constructs. There was no significant difference in ultimate strength between constructs. Ultimate displacement was reduced in the plated constructs. Stiffness did not differ between constructs.

Clinical Significance: The novel par-CA construct was biomechanically similar to the T-plate and both were superior to cross pins in resisting micromotion. There was no difference in load at failure between constructs. Dorsal plate fixation for partial carpal arthrodesis is biomechanically superior to cross pin techniques in resisting micromotion. The novel castless par-CA plate permits radial and ulnar carpal bone compression and a more distal location of the plate to limit impingement and placement of screws in two metacarpal bones. These design features may reduce the risk of implant impingement and loosening as well as negating complications associated with postoperative coaptation.

Introduction

Compromise to the canine carpal palmar fibrocartilage and ligaments most commonly occur due to traumatic hyperextension injury often sustained from a jump or fall ^{1,2}. An inherited degeneration has also been reported in breeds such as the Shetland Sheep Dog and Border Collie ³. Carpal hyperextension injuries may affect the antebrachiocarpal, middle carpal or carpometacarpal joints either in isolation or concurrently, with concurrent middle carpal and carpometacarpal injury being most common ^{4,5}.

In the case where antebrachiocarpal palmar support is not compromised, partial carpal arthrodesis, comprising fusion of the middle carpal and carpometacarpal joints has been advocated to re-establish palmar stability and limb function ⁶. Partial carpal arthrodesis carries the biomechanical advantage over pancarpal arthrodesis of maintained antebrachiocarpal motion during gait with typically 76° or approximately 50% of carpal flexion being maintained postoperatively ^{7,8}.

Techniques described for management of antebrachiocarpal hyperextension injuries include immobilisation in a flexion cast ^{2,9}, and partial carpal arthrodesis via intramedullary (IM) pinning ^{2,10}, a dorsally applied T-plate ¹¹, dorsal twin plating ^{2,10-12} and cross pinning ⁷. Early reports of management by coaptation cannot be advocated as this predictably results in unsatisfactory clinical results with persistence of hyperextension ^{6,13} as do attempts at primary ligament repair or augmentation techniques utilising wire or autogenous fascia ^{4,5,14}.

Widely variable results have been reported clinically for dogs undergoing partial carpal arthrodesis with between 50% to 100% success rates described ^{10,12}. Some reports describe inferior limb function following partial carpal arthrodesis when compared to the clinical results that can be achieved with pancarpal arthrodesis ¹². However, such claims have recently been refuted in a study employing objective gait analysis. ⁸ Poor clinical results with partial carpal arthrodesis have been attributed to multiple factors including poor case selection ¹⁰ the development of antebrachiocarpal osteoarthritis ¹² as well as implant loosening, migration or breakage ^{7,10}.

An important factor that may influence the success of surgery is the arthrodesis technique employed. Compression and immediate rigid internal fixation are prerequisites for successful arthrodesis ¹⁵. Partial carpal arthrodesis techniques that do not strictly adhere to these principles such as cross and intramedullary pinning may predispose to delayed or incomplete fusion of carpal bones. Similarly those that do not rigidly immobilise both the ulnar and radial carpal bones such as dorsal T plating or IM pinning could predispose to antebrachiocarpal joint incongruity, production of aberrant callus and the development of osteoarthritis. In addition, external coaptation has been recommended following arthrodesis for between four and six weeks postoperatively to avoid implant failure ¹⁵. Unfortunately a need for prolonged coaptation is frequently associated with significant postoperative complications compromising short and long term limb function ^{7,16-18,11}. To date, there is currently no castless implant system available for canine partial carpal arthrodesis allowing rigid internal fixation with compression of the proximal row of carpal bones, intercarpal and carpometacarpal joints, thus fulfilling the criteria to promote expedient arthrodesis. There are similarly no biomechanical studies evaluating the effectiveness of different canine partial carpal arthrodesis techniques. The aims of this study were to present a novel castless canine partial carpal arthrodesis plate (par-CA) and to perform an *ex-vivo* biomechanical comparison of this plate with previously described T-plate and cross pin arthrodesis techniques.

Materials and Methods

Implant considerations

The Par-CA implant was developed based on perceived clinical and surgical shortcomings of available implant systems for partial carpal arthrodesis. The prototypes were manufactured from 316LVM stainless steel (Figure 1). The proximal aspect of the plate was bevelled by 60 degrees and laterally recessed 20 degrees to avoid impingement on both the cranio-distal aspect and styloid process of the radius respectively during carpal extension. Three holes were incorporated proximally (1 – 3); a central hole (2) accepting a screw in neutralisation placed in the radial carpal bone and oval compression holes (1 or 3) allowing placement of both a second screw in buttress in the radial carpal bone and a third screw in the ulnar carpal bone placed in compression towards the radial carpal bone. Holes 1 – 3 were angled 60 degrees proximally allowing more distal placement of the plate on both the radial and ulnar carpal bones to avoid impingement on the plate by the radius during extension of the antebrachiocarpal joint. A single 0.9 millimeter (mm) hole perforating the plate immediately below the central round hole allowed a small Kirschner wire or hypodermic needle to be placed through the plate into the space immediately distal to the radial carpal bone to define the optimum proximo-distal position of the plate and maintain alignment of the plate during screw placement. The distal

component of the plate incorporated design features of a previously described castless plate for pancarpal arthrodesis;¹⁹ with six progressively divergent 2.7mm screw holes engaging metacarpal bones three and four, a keel underside to the plate increasing dorsal metacarpal contact with the implant and two further 0.9mm alignment holes facilitating axial alignment of the distal plate. The plate was similarly tapered distally reducing any stress riser at this site. The distal component of the plate was designed to span approximately 60% of the length of metacarpal III and IV in accordance with previously published guidelines for carpal arthrodesis (Whitelock 1999).

Cadaver limb preparation and surgical technique

11 pairs of greyhound forelimbs were obtained from dogs euthanatized for reasons unrelated to the study. Individual dogs were weighed and then the forelimbs disarticulated at the elbow joint, wrapped in saline soaked gauze swabs, individually bagged, archived and stored at -20°C. Limbs were allowed to thaw for 12 hours prior to implant placement and biomechanical testing.

Limbs were divided into four groups; control (4 limbs), cross pins (6 limbs), T-plate (6 limbs) and par-CA (6 limbs). For the control limbs no implants were placed. For the cross pin limbs, two 1.6 mm cross pins were applied to the carpus in accordance with a previously published partial carpal arthrodesis surgical technique⁷. For the T-plate limbs, a seven hole 2.7 mm T-plate (VP1342.09, Synthes Vet, U.K.) was applied to the dorsal aspect of the radial carpal and third metacarpal (MCIII) bones in accordance with a previously described technique¹¹, the plate length being chosen to span at least 60% of MC III length. For the par-CA limbs the prototype plate was applied in accordance with the published user guide for this plate (<http://www.orthomed.co.uk/pdf-downloads.html>). Following placement of all three implant constructs a palmar approach was made to the middle carpal and carpometacarpal joints²⁰ and the palmar carpal fibrocartilage and palmar ligament support sectioned at these levels. Care was taken to ensure that the palmar ligament and fibrocartilage support to the antebrachiocarpal joint was not compromised. Palmar ligaments and fibrocartilage were not sectioned in the control group. The palmar process of the radial carpal bone and palmar aspect of MCIII bone were then exposed with a periosteal elevator and two 1.5 mm holes drilled in these bones. A linear-motion potentiometer (8FLP10A conductive plastic precision linear-motion potentiometer, Sakae-Tsushin-Kogyo Ltd, Kanagawa-ken, Japan) was applied to the palmar aspect of the radial carpal bone and MCIII with 2.0 cortical screws to measure micromotion between the bones (Figure 2). The soft tissue was then removed from the proximal third of the radius and ulna with a periosteal elevator and the bones transversely osteotomised in the proximal metaphyseal region after which the remaining proximal 6 – 8 cm of the radius and ulna were potted vertically in a bespoke steel square fixture with dental plaster (Dentstone KD, BPB Formular, Newark, Notts, UK). The limb was then loaded using a HC10 servo-hydraulic Universal Testing Machine (Dartec-Zwick-Roell LTD, Leominster, Herefordshire, UK) (Figure 3). The paw was constrained by clamping the phalanges beneath a steel plate to immobilise the digits during carpal loading. Rigid immobilisation of the paw was confirmed once each limb was mounted in the testing machine and loading commenced.

Biomechanical parameters measured were micromotion between carpal and metacarpal bones and ultimate strength, ultimate displacement and stiffness. Micromotion is the recoverable relative movement between implant and bone associated with the elasticity of the construct and is often used along with migration to quantify the postoperative stability of orthopaedic implants²¹.

Experiment 1: Assessment of construct micromotion

Load was applied to each limb at 30% of individual cadaver bodyweight at a frequency of 1 Hertz (Hz) for a total of 10,000 cycles to represent a typical postoperative period prior to fusion²² and palmar displacement data recorded via the potentiometer. Loading at 30% of total bodyweight was chosen to represent load in a standing dog based on previous gait studies identifying 60% of bodyweight to be distributed between the thoracic limbs²³. The output of the potentiometer was digitised using a 12-bit A/D converter (DT2821, Data Translation, Inc. Morlboro, MA), and the resultant data captured at 20 Hz using HP-VEE v5.01 software (Agilent Technologies UK Ltd, Edinburgh, Scotland). The voltage signal was calibrated against known displacements made using a bench micrometer. Data was imported into Excel (Microsoft, Redmond, Washington USA 2007) and the micromotion value for each construct defined by the difference between maximum / minimum micromotion displacement values (μms) calculated at the 2000 second time interval (corresponding to the 10000th cycle of micromotion) for each construct (Figure 4).

Experiment 2: Assessment of construct ultimate strength, ultimate displacement and stiffness

Subsequent to collection of micromotion data limbs were loaded to failure at a rate of 20 millimetres per second until failure of the construct occurred in each case. The ultimate strength, defined as the maximum force each construct could withstand before failure was recorded in kilonewtons (kN). Ultimate displacement, defined as the maximum displacement of the construct before failure was recorded in mm. Stiffness, defined as the gradient of the linear region of the force-deformation graph for each construct was recorded in kN/mm.

Following failure of each construct limbs were radiographed and dissected if necessary to determine the mode of failure of each construct.

Statistical analysis

Analysis was performed using GraphPad InStat (Version 3.06 for Windows 95, GraphPad Software, San Diego California, USA, www.graphpad.com). For each construct (control group, cross pins, T-plate and par-CA) data was assessed for normality using the Kolmogorov-Smirnov test and subsequently either a parametric analysis of variants (AVOVA) with Tukey post hoc test or a Kruskal-Wallis (nonparametric ANOVA) with Dunn post hoc test performed. ANOVA's assessed for a significant difference (defined as $p < 0.05$ for all statistical comparisons) between each cohort for the parameter defined (i.e. micromotion, load to failure, ultimate displacement and stiffness) with post hoc tests performed when significance was achieved. In the case of normally distributed data 95% confidence intervals (CI), standard deviations (SD) and means were defined. For data that was not normally distributed 95% frequency intervals (FI) and medians were defined.

Results

Experiment 1: Assessment of construct micromotion

Data obtained from all four groups (control, cross pin, T-plate and par-CA) was normally distributed. The mean micromotion for the control limbs was $120.63\mu\text{m}$ (CI 90.35 to 150.9, $SD \pm 19.02$), cross pins mean $266.93\mu\text{m}$ (CI 132.59 to 401.27, $SD \pm 127.99$), T-plate mean $84.95\mu\text{m}$ (CI 8.85 to 161.06, $SD \pm 72.51$) and prototype plate mean $78.07\mu\text{m}$ (CI 31.34 to 124.79, $SD \pm 44.52$). The ANOVA revealed a statistically significant difference in micromotion between K wire and T-plate ($P < 0.01$) and K wire and par-CA plates ($P < 0.01$). There was no significant difference between control and K wire, control and T-plate, control and par-CA plate and T-plate and par-CA plate constructs.

Experiment 2: Assessment of construct ultimate strength, ultimate displacement and stiffness

Data obtained for ultimate strength for all four groups (control, cross pin, T-plate and par-CA) was normally distributed. The mean ultimate strength of the control limbs was 0.83kN (CI 0.49 to 1.17 $SD \pm 0.22$), cross pins mean 0.99kN (CI 0.52 to 1.45, $SD \pm 0.45$), T-plate mean 0.97kN (CI 0.81 to 1.12) and par-CA mean 1.33kN (CI 0.87 to 1.79). The ANOVA did not reveal a statistically significant difference between groups (Figure 5).

Data obtained for ultimate displacement was not normally distributed. The median ultimate displacement of the control limbs was 39.3mm (FI 30.3 to 49.6), cross pins median 19.5mm (FI 18.3 to 26.9), T-plate median 15.7mm (FI 6.4 to 22.7) and par-CA median 17.0mm (FI 15.5 to 24.4). The ANOVA revealed a statistically significant difference between control and T-plate constructs and control and par-CA constructs with both plated constructs having significantly reduced ultimate displacement.

Data obtained for stiffness for all groups was not normally distributed. The median stiffness of the control limbs was 0.047kN/mm (FI 0.012 to 0.054), cross pins median 0.079kN/mm (FI 0.025 to 0.262), T-plate median 0.124kN/mm (FI 0.062 to 0.428) and par-CA median 0.122kN/mm (FI 0.053 to 0.259). The ANOVA did not reveal a statistically insignificant difference between groups.

Mode of failure of each construct was determined by orthogonal radiographs and dissection of each limb following testing. All limbs failed by rupture of the palmar antebrachicarpal fibrocartilage. In the cross pin group there was no evidence of implant migration or fracture. One of the T-plate constructs developed a fracture of MC III distal to the plate and in another the radial carpal bone screw loosened (Figure 6). Fracture or implant loosening did not occur in any of the par-CA constructs.

Discussion

The results of this study demonstrate that the par-CA and T-plate constructs were biomechanically similar and appear superior to cross pinning in reducing intercarpal and carpometacarpal micromotion. Whilst there was no difference in ultimate strength or stiffness tests between constructs; dorsal plating allows compression of the intercarpal and carpometacarpal joints which is not achievable with cross pinning. A

degree of axial micromotion has been shown to be advantageous in the promotion of pancarpal arthrodesis employing circular skeletal fixation²⁴⁻²⁶. However, in a case series of 21 carpi undergoing partial carpal arthrodesis with cross pins⁷ whilst all carpi ultimately achieved arthrodesis, 22% had incomplete intercarpal fusion, 30% had implant migration postoperatively, and 9% suffered progressive carpal collapse revealing significant morbidity with this technique. Failure of arthrodesis or implant migration are complications that have not been reported with any frequency in cases arthrodesed with either straight dynamic compression plates (SDCP) or T-plate fixation^{11,12}. However, shortcomings of dorsal plating techniques include impingement of the plate on the radius¹², an inability to provide radio-ulnar carpal bone compression and the recommendation to employ coaptation for six weeks postoperatively^{11,12}. The par-CA used in this study is designed to not require coaptation postoperatively, to allow direct radio-ulnar carpal bone compression facilitating primary bone healing and to permit more distal attachment of the plate than either SDCP or T-plating to abolish radial impingement during carpal extension. Circumventing the need for coaptation following partial carpal arthrodesis surgeries is advantageous as morbidities of up to 35% have been reported⁷. Clinical evaluation of the par-CA is required to evaluate these design objectives clinically. It is arguable that partial carpal arthrodesis via palmar plating may be biomechanically superior to dorsal plating as implants span the tension side of the carpus, as well as avoiding plate impingement in carpal extension. Palmar plating for pancarpal arthrodesis has been described in a small case series²⁷. However, this surgical approach is technically challenging and plate impingement on the radius in carpal flexion may be a concern. In a similar respect to dogs, plating is commonly employed in partial wrist fusion in humans. Hyperextension injuries in humans occur most commonly due to a fall of the patient on to an outstretched hand with the most common injury being scapholunate ligament injury²⁸. Partial wrist arthrodesis is also commonly employed for the alleviation of pain attributable to osteoarthritis²⁹. Dorsal plating techniques such as the use of the Spider plate (Spider Limited Wrist Arthrodesis System; Kinetikos Medical, San Diego, CA, U.S.A.) appear to offer superior results in selected cases of wrist arthrodesis²⁹ when compared to arthroscopic Kirschner wire or cannulated screwing or open approach stapling and intramedullary pin techniques³⁰. It is interesting to note that as part of the surgical technique for dorsal plating in humans, the plate is recessed in a channel within the bone to negate the risk of impingement of the implants on bone when the wrist is extended²⁹. Such techniques for recessing plates have so far not been investigated in the canine carpus.

There are limitations to this *ex vivo* study. Firstly, our *ex vivo* limbs did not accurately mimic the movement of the thoracic limb as would be observed clinically. We elected to immobilise the digits of the foot during limb testing to stop the manus slipping whilst the limb was loaded, thus movement of the distal limb bore no resemblance to the angular excursion the foot would move clinically, and thus the moments generated by the distal limb during stance. Secondly, we elected to test each construct with the limb in a standing position and with standing bodyweight applied in pure axial compression. Forces applied to the carpus and implants in the walking and running dog would be greater than those at rest but the precise forces acting through a partial fused carpal joint as a function of different activity levels are currently ill defined.

In summary, the par-CA plate and T-plate constructs were similar and superior to cross pinning in resisting micromotion. There was no difference in ultimate strength or stiffness between constructs. Ultimate strength was increased in plate specimens compared to control and cross pin specimens. The par-CA plate is designed to allow radio-ulnar carpal bone compression and more distal plate application than with T-plate fixation. These features, combined with a design which may negate the need for postoperative coaptation may reduce morbidity previously associated with canine partial carpal arthrodesis. Clinical trials of the par-CA implant are required to evaluate its clinical efficacy.

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Figure 1: The par-CA (prototype) plate is shown: Dorsal, ventral, lateral (left to right). The proximal aspect of the plate is bevelled by 60 degrees and laterally recessed with holes 1 – 3 angled at 60 degrees to permit lower placement of the plate on the radial and ulnar carpal bones and avoid impingement of the distal radius on the plate in full extension. The plate engages both radial and ulnar carpal bones and permits their compression to encourage primary bone healing at this site. Holes 4, 6, 8 and 5, 7, 9 diverge engaging metacarpals III and IV and the plate has a keel increasing metacarpal contact



Figure 2: Following placement of the arthrodesis implants the palmar process of the radial carpal bone and palmar aspect of the third metacarpal bone were exposed and a potentiometer applied using 2.7mm screws to the palmar aspect of these bones

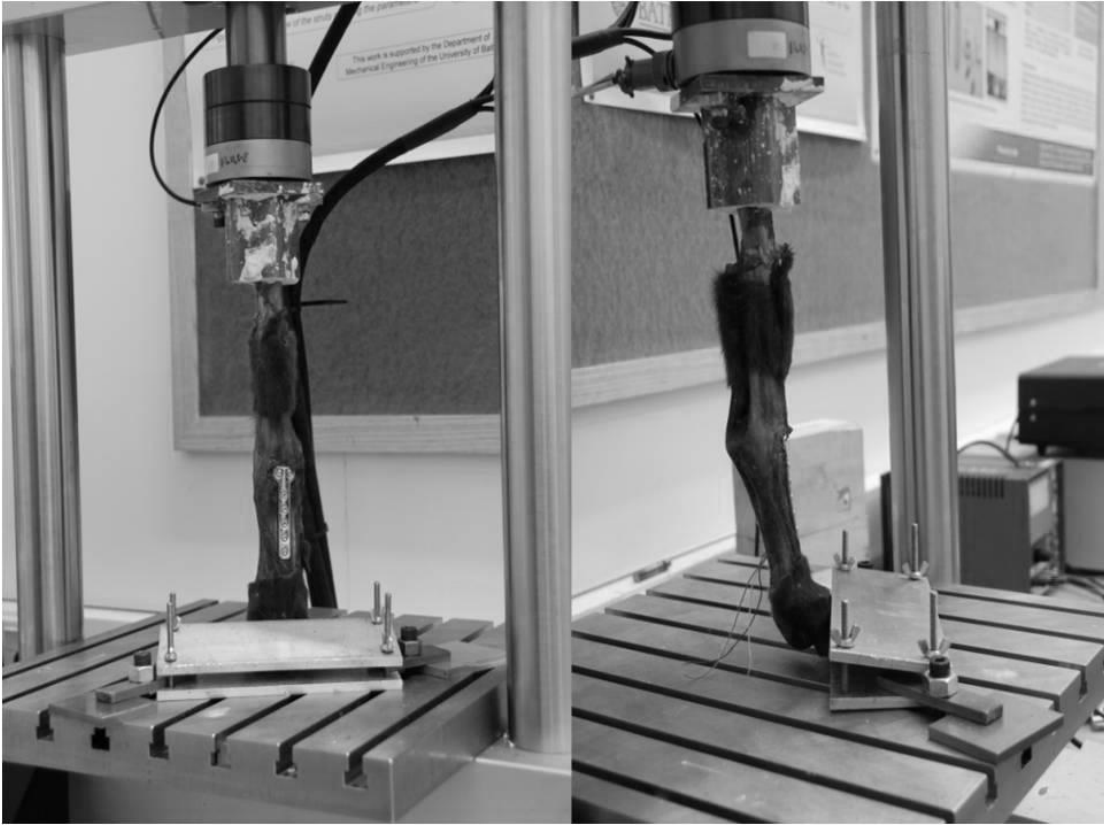


Figure 3: The prepared limb construct in the load cell prior to the onset of mechanical testing.

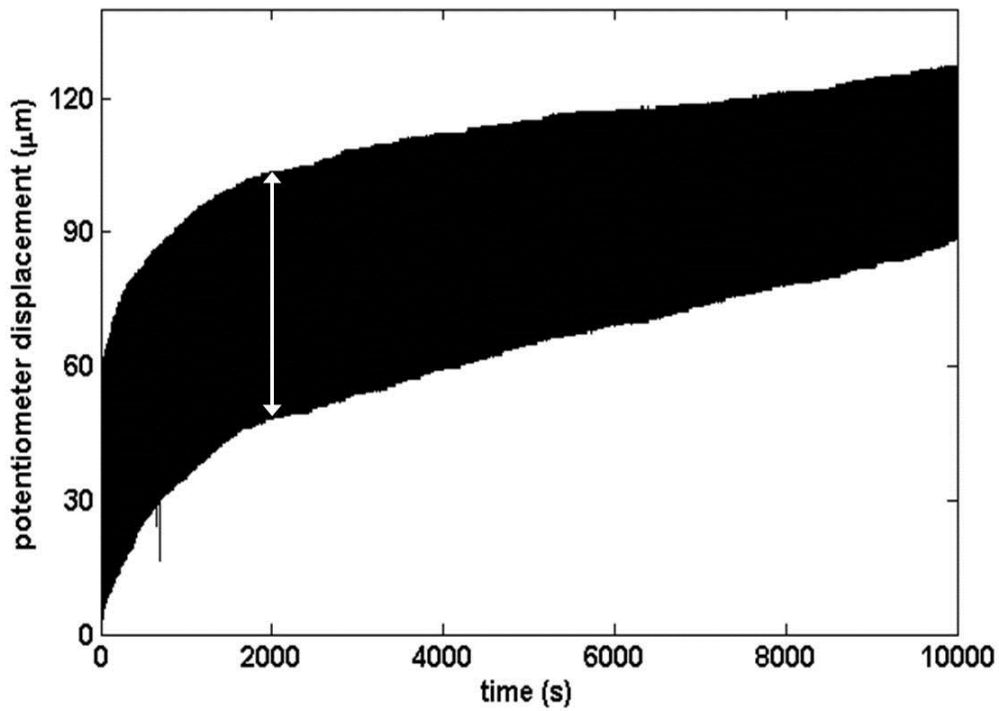


Figure 4: Typical displacement trace for a limb construct as defined by potentiometer displacement micrometers (μm) with time (seconds). The amount of micromotion measured is shown by the white arrow.

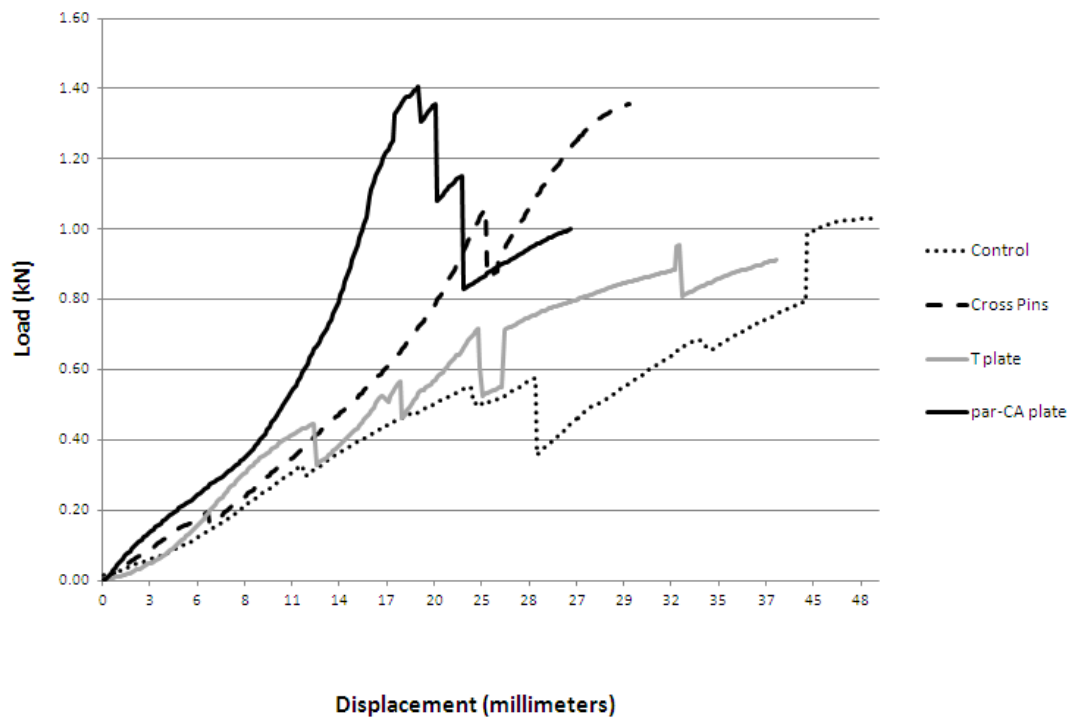


Figure 5: Graph showing mean load - displacement data for the control, cross pins, T-plate and par-CA plate constructs.



Figure 6: Radiograph (left) and photograph (right) of two of the T-plate constructs demonstrating metacarpal III fracture (thin white arrow) and loosening of a radial carpal bone screw (thick white arrow).